



On the discontinuous nature of the Mozambique Current

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The concept of a spatially continuous western boundary current in the Mozambique Channel has historically been based on erroneous interpretations of ships' drift. Recent observations have demonstrated that the circulation in the Channel is instead dominated by anti-cyclonic eddies drifting poleward. It has therefore been suggested that no coherent Mozambique Current exists at any time. However, satellite and other observations indicate that a continuous current – not necessarily an inherent part of Mozambique Eddies – may at times be found along the full Mozambican shelf break. Using a high-resolution, numerical model we have demonstrated how such a feature may come about. In the model, a continuous current is a highly irregularly occurring event, occurring about once per year, with an average duration of only 9 days and with a vertical extent of about 800 m. Surface speeds may vary from 0.5 m/s to 1.5 m/s and the volume flux involved is about 10 Sv. The continuous current may occasionally be important for the transport of biota along the continental shelf and slope.

Introduction

The major western boundary current of the South Indian Ocean, the Agulhas Current, has traditionally been considered as continuously connected to the Mozambique Current to the north.¹ Observations of ships' drift have indicated^{2,3} that strong poleward movements are found along the east African coast all the way from the northern tip of the Mozambique Channel to the southern tip of Africa. These Eulerian measurements have then usually been interpreted as reflecting the existence of an unbroken current along this whole coastline. Depictions of average geostrophic currents,⁴ based on all existing hydrographic data, also show a clear continuum.

Investigations by Lutjeharms⁵ and Sætre and Jorge da Silva⁶, using a compilation of quasi-synoptic hydrographic data from a number of research cruises, have suggested that the circulation could be considerably more complicated, but this result, as it was based on observations from an eclectic collection of cruises, did not fundamentally alter the existing view that there was a Mozambique Current.⁷ A numerical model study⁸ demonstrated that the increased level of eddy kinetic energy seen in satellite altimetry could be explained by the existence of mesoscale eddies. Shortly after, a cruise specifically dedicated to an investigation of the nature of the Mozambique Current⁹ was unable to find a continuous current and instead demonstrated that the channel was populated by a street of strong, anti-cyclonic eddies slowly moving poleward. Subsequent studies,^{10,11,12} using mostly current observations in the narrows of the channel and anomalies of sea surface height, have emphatically confirmed these conclusions. These eddies have been seen to form mostly at the narrows of the channel or directly equatorward of here.^{11,12,13} A modelling study¹⁴ has shown that the obstruction formed by the land mass of Madagascar precludes the formation of a proper western boundary current in the channel.

How important is the absence of a continuous western boundary current in the Mozambique channel? On a regional level, it has been shown that Mozambique Eddies carry coastal chlorophyll into the centre of the channel,¹⁵ which an undisturbed western boundary current would not do, and that this might have an influence on the breeding success of local marine birds.¹⁶ Furthermore, it has been shown¹⁷ that birds such as great frigate birds forage preferentially at the edges of these eddies, suggesting that there are also concentrations of tuna at the fronts so formed, because the presence of these animals is closely related. Apart from the perceived impact of eddies on the ecosystem, it has also been demonstrated that these eddies have an impact on the Agulhas Current downstream.¹⁸ Eddies drifting poleward may trigger cyclonic perturbations such as the Natal Pulses at the coastline of South Africa near 30°S, causing subsequent shedding of Agulhas Rings south of Africa and thus controlling interocean heat and salt exchange.¹⁹ The existence and importance of Mozambique Eddies is therefore not in doubt. However, there does seem to be some evidence for an intermittent, continuous flow along parts of the African coastline in the Mozambique Channel.^{6,20} Using satellite remote sensing and modelling simulations, we established some evidence for such occurrences, their frequency, location and durability.

Data and methods

An inspection of satellite remote sensing products for the Mozambique Channel demonstrates their limited utility here. Instantaneous thermal infrared images of sufficiently large parts of the channel to identify a continuous coastal current are scarce as a result of enduring and extensive cloud cover and are very seldom of sufficient duration to test the persistence of any circulation feature. This limitation also holds for ocean colour images.¹⁵ Furthermore, surface heating during spells of weak winds rapidly removes any surface temperature contrast. Hence such images can mostly be used for illustrative purposes only (e.g. Figure 1). If a continuous Mozambique Current were to exist, it would most probably be hugging the continental shelf³ and thus in most parts be too close to the coast for appropriate investigation using altimetric measurements. As a consequence we largely limit ourselves to analysing model simulations, using a model that represents well a wide spatial range of circulation features in the region.²¹

In this investigation we have used a high-resolution, $\frac{1}{10}^\circ$ model (AG01) of the Agulhas region (20°W–70°E, 47°S–7°S) based on

the Nucleus for European Modelling of the Ocean (NEMO) code.²² It is forced by bulk formulae using daily, interannually varying wind and thermohaline surface forcing fields over the period 1980–2004.²³ Its main, novel element is the ‘two-way nesting’²⁴ of the regional model into this coarser, well-established global model.²¹ The nesting approach allows one to study the effect of outside perturbations on the mesoscale components of the greater Agulhas circulation.¹⁹ One of these components is the circulation in the Mozambique Channel where outside perturbations have been shown to be particularly important.¹⁰ The model features partially filled bottom cells (46 levels) and advanced advection schemes which have been shown to be crucial elements of a reasonable simulation of the Agulhas regime.²⁵ More technical detail on the model can be found in Biastoch et al.²⁶

Current measurements across the narrows of the channel were from the LOCO (Long-term Ocean Climate Observations) mooring array. Detail on the disposition of this array and the precision of its measurements can be found in Harlander et al.¹²

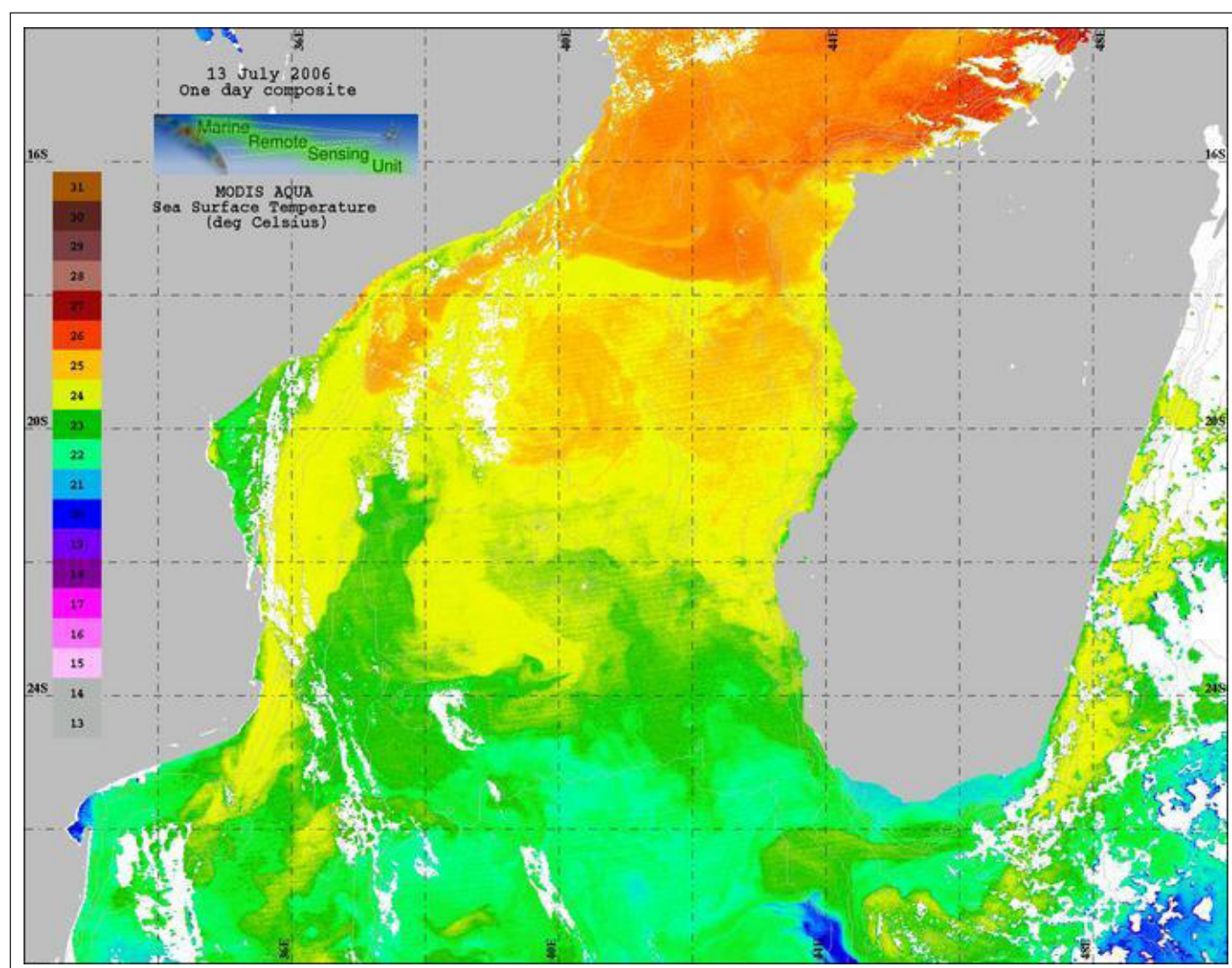


FIGURE 1: Thermal infrared image of the sea surface temperature from the MODIS AQUA satellite showing an extensive, warm current along the entire Mozambican continental shelf. The image is for 13 July 2006 with temperatures given on the scale. This image is a one-day composite thus limiting cloud cover to the white areas.

Results and discussion

Figure 1 shows an example of a tongue of warm water extending along a significant portion of the Mozambican shelf. The width of this plume varied, but is estimated to have been at least 100 km along its full length. It extended from 14°S to 27°S, a distance of about 1500 km. Although the sea surface temperature on this occasion suggests a number of other circulation features in this part of the Mozambique Channel, there seems to be no compelling evidence that this plume was in any way connected to the Mozambique Eddies and that instead it was a continuous current.

The model simulation in Figure 2a shows a comparable portrayal, but in surface velocities. Here the current extends uninterruptedly from the northern to the southern mouth of the Mozambique Channel. This simulation is in sharp contrast to the more characteristic portrayal in Figure 2b. Here the circulation consists of three well-developed Mozambique Eddies, all about 300 km in diameter (comparable to those found by De Ruijter et al.⁹), with one being formed at the narrows at the time. The continuous current in Figure 2a is relatively slow in its far northern part (0.5 m/s), but increases in velocity downstream with two maxima in speed (up to 1.4 m/s) at 16°S – the narrows of the Channel – and at 22°S. The current follows the shelf edge (~100 m depth) quite closely, overshoots the Delagoa Bight (25°S) and feeds directly into the Agulhas Current to the south (28°S) as one continuous current. There is evidence of cyclonic eddy activity in the channel at the time of the simulation shown in Figure 2a, and a suggestion that the current is enhanced in strength by these eddies at the two locations where the speeds are highest. However, there is no obvious relationship between these eddies and the full, extended current. The prevalence of such a continuous current and the frequency of its occurrence are unknown.

An analysis of 25 years of model simulations indicates that the occurrence of a continuous current is atypical, intermittent

and highly irregular. During this period it was observed 21 times, but during a previous period of 14 years there was no evidence of such a feature at all, leading to an average of 0.84 times per year with a standard deviation of 1.14. The average duration of a continuous current was 9 days (± 5) with a mode of less than 5 days (11 out of 21 of the occurrences). These results suggest that it is a very short-lived event. In all cases, the continuous current breaks up into a string of eddies, particularly at the narrows of the channel and at 24°S, just upstream of the Delagoa Bight. However, eddies can be formed along the full length of the channel²⁷ at the break-up of a current event.

The vertical structure of such a current is shown in Figure 3. The simulated current on this occasion had a surface speed of up to 1.1 m/s, had a well-developed undercurrent^{9,26} and extended to a depth of 800 m. The flow on this occasion may have been partially as a result of an anti-cyclonic eddy with its centre at about 42°E (Figure 2) with a maximum surface speed in its eastern rim of 0.45 m/s. If this eddy was largely symmetrical, it would mean that the current itself had a top speed of 0.65 m/s. This speed is comparable to the observed current speeds in the narrows of the channel. The example shown in Figure 3b exhibits strong southward flow along the Mozambican shelf break, also to a depth of about 800 m. The surface speed was 0.9 m/s contrasting with a weak northward flow in the eastern side of the channel where the maximum speeds were only about 0.2 m/s. This northward flow strengthened so that 15 days later there was a fully developed, anti-cyclonic eddy in the narrows of the channel, but still enhanced on the western side. During a 4-year record for the LOCO moorings there were five occasions when the surface speeds could be considered as not belonging to the surface expression of an eddy. However, on two of these occasions a subsurface eddy (at 1000 m) complicated the structure.

The volume transport along the full length of the modelled continuous current is given in Figure 4, based on what is

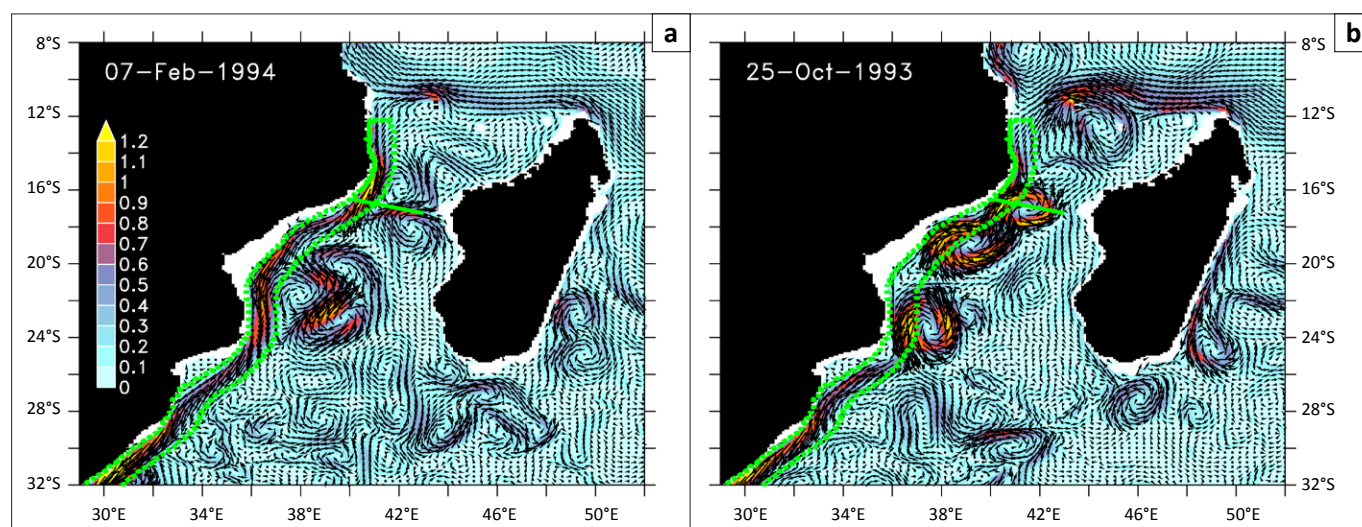


FIGURE 2: Simulated velocities in the Mozambique Channel at a depth of 93 m in the NEMO model for (a) 07 February 1994 and (b) 25 October 1993. (b) Shows the normal current configuration in which three strong anti-cyclonic eddies are evident, all heading poleward. In contrast, (a) presents the more unusual case of a continuous current along the full length of the Mozambican shelf; this current on this occasion stayed intact for about 5 days. The geographic locations of a vertical speed section across the simulated current at 16°S (Figure 3) and the coastal-following section (Figure 4) are shown by green lines. Arrows indicate current directions.

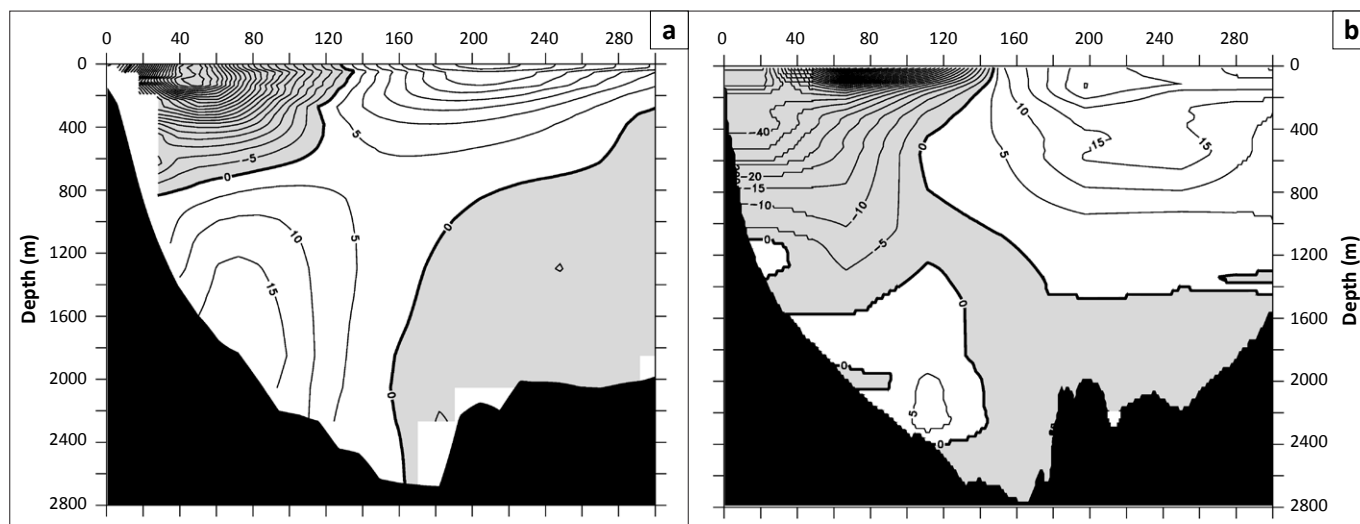


FIGURE 3: (a) A vertical speed section across a simulated Mozambique Current on 07 February 1994 in the NEMO model simulation (equatorward motion is indicated in grey; contour interval is 5 cm/s). The section was at 16°S latitude (see Figure 2). (b) A comparable speed section from the Long-term Ocean Climate Observations (LOCO) mooring array at about the same location for 29 June 2005 when there was evidence of a Mozambique Current.

observed in the green box in Figure 2. There is a gradual increase from 0 Sv ($10^6 \text{ m}^3/\text{s}$) at the northern mouth (12°S) to 21 Sv at 29°S with peaks at the locations where anti-cyclonic eddies are juxtaposed with the current (16°S, 22°S). Including the flux of the undercurrent reduces the volume transport of the current by about 5 Sv – 12 Sv, larger than that measured for the undercurrent by De Ruijter et al.⁹ The sharp inflection point at 29°S suggests that this is where the Agulhas Current starts and the total transport, including that of the undercurrent, rapidly rises to 72 Sv, comparable to that observed.^{26,28} The increasing volume transport and depth of the current makes the inclusion of the Agulhas Undercurrent relatively less relevant downstream, so increasing the depth of integration to 1000 m increases the total volume transport south of 29°S, in contrast to that in the Mozambique Channel.

Conclusions

Based on a 25-year simulation of the circulation in the Mozambique Channel, supported by a few observations from

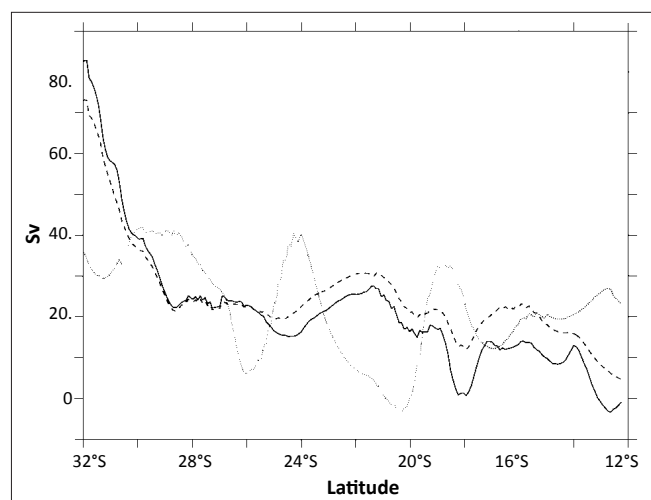


FIGURE 4: The volume transport (in Sv), integrated along a coastal-following section over the full length of a Mozambique Current on 07 February 1994 (see Figure 2). The broken line represents the transport to a depth of 800 m and the continuous line represents the full depth integral. The grey line represents the transport (over the full depth) on 23 October 1993.

satellite and current meter moorings, we have reached the conclusion that a continuous western boundary current along the Mozambican shelf edge may on occasion come about, but that this is a very exceptional event that invariably lasts for only a short time. It therefore probably plays a negligible role in the channel throughflow but it may occasionally open a ‘window’ for the transport of biota, such as larvae, along the continental shelf and slope.

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Prof. Emeritus Johann R.E. Lutjeharms, colleague, mentor and friend, passed away on 08 June 2011.

Competing interests

We declare that we have no financial or personal relationships which may have inappropriately influenced us in writing this article.

Authors' contributions

Dr Ridderinkhof and Prof. De Ruijter were responsible for the current mooring project and data. Dr Van der Werf analysed the current meter data; Dr Biastoch designed and ran the general ocean circulation model; and all authors contributed to the concept of the investigation and the writing of the manuscript.



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